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High-Energy Soliton Dynamics in Gas-Filled Hollow Capillary Fibers

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Abstract: We show that soliton dynamics scale to millijoule energies and terrawatt peak powers in simple hollow capillary fibers. We numerically model sub-femtosecond pulse self-compression, and experimentally demonstrate high-brightness μJ -scale ultraviolet (125-330 nm) pulse generation.
OCIS codes: 190.5530, 260.7210, 320.7110

Self-phase modulation (SPM) based pulse compression in large-core (100 μm to 1 mm diameter) hollow capillary fiber (HCF) is the established route to generate the high-energy few-cycle pulse sources required for high-field experiments [1]. In such experiments the HCF is used purely for nonlinear phase modulation, and the weak linear dispersion is largely neglected. In this paper we demonstrate that, by carefully combining both nonlinear and dispersive effects, soliton dynamics can be harnessed in HCF. Most of the ultrafast soliton effects demonstrated in recent years in gas-filled hollow-core microstructured fibers (such as anti-resonant guiding, kagome-style photonic crystal fiber) [2, 3], can be significantly scaled in energy by using HCF, by at least two orders of magnitude. Here we numerically and experimentally explore coherent soliton self-compression, leading to sub-femtosecond pulse durations, multi-octave supercontinuum generation and subsequent fission dynamics. In particular, we experimentally demonstrate resonant dispersive-wave emission in the deep (DUV) and vacuum (VUV) ultraviolet (130-330 nm), with preliminary estimates of the emitted DUV pulse energies exceeding 8 μJ .

For resonant dispersive-wave emission to occur at extreme frequencies, the pump pulse must undergo soliton-effect self-compression until it reaches a sub-femtosecond pulse duration and a multi-octave spanning spectral width [2, 3]. At this point a resonant transfer of energy can occur to particular phase-matched frequencies. This compression and emission point approximately occurs at the soliton fission length $L_{\text{fiss}} = L_d/N$, where L_d is the dispersion length and N the soliton order [4]. For HCF it can be shown that $L_{\text{fiss}} \propto \tau_0^2 a^2/N$, where τ_0 is the pump pulse duration and a is the HCF core radius. In microstructured fibres, the low guidance loss for small a allows one to achieve soliton self-compression and fission in short length scales. In conventional HCF, the large a means that either very large length scales are required, or short pump pulses. Following the pioneering work of Nagy et al. [5], we make use of 3 m long stretched capillary fibers, to extend the length scale over which soliton dynamics can occur, and pump with 10 fs pulses from a conventional HCF compressor system to reduce L_{fiss} .

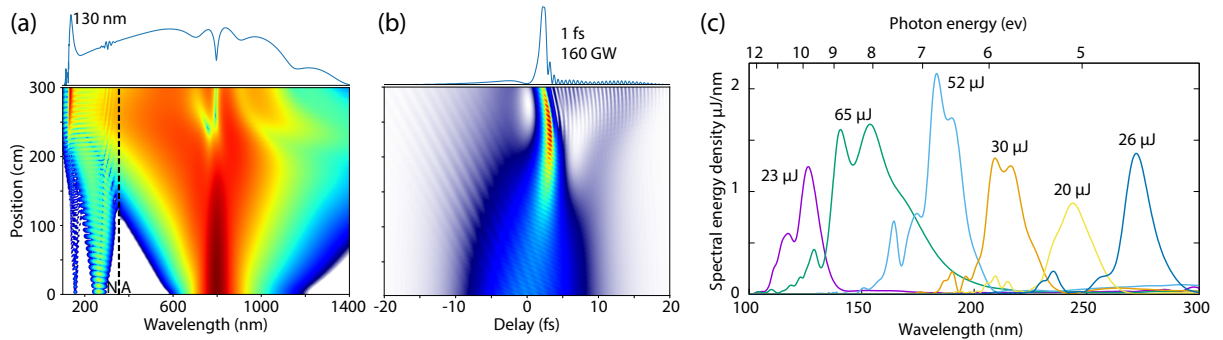


Fig. 1. Numerically modelled spectral (a) and temporal (b) evolution of a 10 fs, 800 nm, 0.5 mJ pump pulse in a 250 μm inner diameter HCF filled with 0.3 bar He. N, A indicate normal and anomalous dispersion regions. (c) Optimized VUV dispersive-wave emission peaks, for different He gas pressures.

Fig. 1(a,b) shows one example simulation using our rigorous, fully vectorial and spatially resolved, unidirectional pulse propagation code, which includes ionization, plasma effects, self-focusing, and polarization effects. A wide range of parameters have been modelled and will be presented, but this example is illustrative, and coincides with the experiments described below. In this case we show the self compression of a 10 fs, 800 nm, 0.5 mJ pump pulse to 1 fs, in a 250 μm inner diameter HCF filled with 0.3 bar He. For these parameters, the zero dispersion point is at 355 nm, and soliton order is $N = 2.5$. Scaling these dynamics to the multi-mJ, terrawatt-power regime is realistic in larger core HCF, and will be presented. At the self-compression point, generation of a dispersive-wave at 130 nm occurs. The energy transfer to the VUV can be extremely efficient, and we predict VUV pulse energies exceeding 50 μJ in sub-femtosecond pulses, as shown in Fig. 1(c).

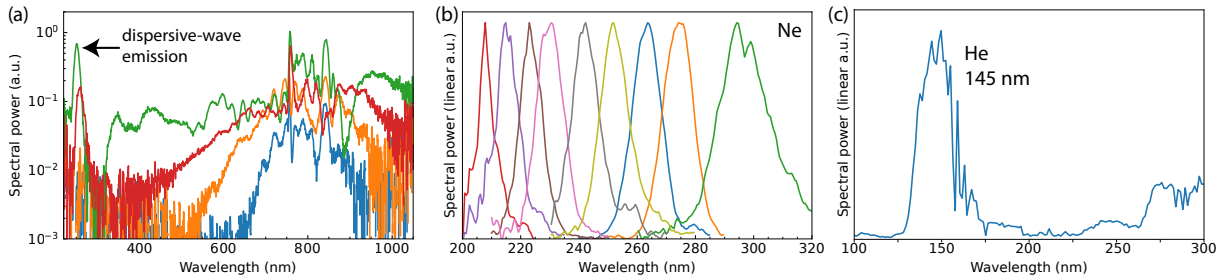


Fig. 2. Experimental results obtained with ~ 10 fs pump pulses in a 3 m long, 250 μm inner-diameter capillary. (a) Evolution of supercontinuum spectrum with increasing pump energy (25 μJ to 300 μJ) in 0.82 bar Ne-filled capillary. (b) Experimental tuning of DUV dispersive-wave emission. Each peak is for a different Ne gas pressure, which ranges from 0.5 bar (short-wavelength peak) to 1.3 bar (long-wavelength peak). For each pressure, the pump energy was chosen in the range from 150 μJ to 300 μJ for optimal dispersive-wave emission. (c) VUV dispersive-wave emission in a 0.6 bar He-filled capillary.

In our experiments, bandwidth limited pulses at around 800 nm, with a duration tunable from 6 fs to 30 fs, are produced in a conventional hollow fiber compressor system based on a stretched, 1.6 m long, 450 μm inner diameter HCF. The compressed pulse energy can be tuned up to 1 mJ. For the current results, we set the pulse duration to 10 fs, and coupled them into a 3 m long stretched hollow capillary fiber, with an inner diameter of 250 μm . Clear spectral signatures of self-compression were observed (Fig. 2a), leading to the emission of a bright dispersive-wave peak in the VUV or DUV. As is characteristic of dispersive-wave emission, this peak was tunable with both gas pressure and pump power (tuning the linear and nonlinear contributions to the phase-matching condition respectively). Fig. 2b shows the experimentally measured pressure-tunable dispersive-wave emission, for Ne gas pressures ranging from 500 mbar (short-wavelength peak) to 1300 mbar (long-wavelength peak). For each pressure, the pump energy was chosen for optimal dispersive-wave emission, in the range from 150 μJ to 300 μJ . The generated DUV energies from these preliminary results were in the range of 5 μJ to 8 μJ . Fig. 2c shows a preliminary measurement of VUV dispersive-wave emission, spanning 125 nm to 175 nm, in a 0.6 bar He-filled capillary.

When fully scaled, this table-top light source will have a brightness within a few orders of magnitude of a synchrotron in the VUV, with dramatically reduced cost and complexity, but also with a temporal resolution that exceeds free-electron laser systems. The new regime of soliton dynamics discussed here promises to be the basis of a new class of light-sources for ultrafast science.

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